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ARRAY DETECTION OF RIPPLE-FIRED SIGNALS: THE CEPSTRAL F-STATISTIC

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13. ABSTRACT *(Maximum 200 words)*

Time and frequency domain approaches to detecting a consistent pattern of reflections on an ensemble of seismic recordings are developed. Such patterns are characteristic of mining bursts and not of nuclear explosions or earthquakes so that detecting a ripple delay structure can serve as one component for discrimination.

In the frequency domain approach, a generalization of cepstral analysis is used to derive an F-Statistic for detecting delay-fired events. Detrended log spectra are considered as realizations of a stationary process whose periodic components are quefrencies, with periods proportional to delay time differences. An F-Statistic is derived that is proportional to the stacked cepstrum and the spectrum of the stacked log spectra. Advantages of the cepstral F-Statistic accrue from better resolution and the fact that statistical significance can be established for delay peaks. It is also easily incorporated into automatic detection systems.

The frequency domain approach is compared to a time domain approach that involves searching seasonal autoregressive models with a fixed regular delay structure. Simulated array data and data from a number of mining explosions, measured at ARCESS, are analyzed by both approaches.

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1. Introduction

Regional seismic monitoring and discrimination capabilities that are desirable under a potential Comprehensive Test Ban Treaty (CTBT) can be improved by developing algorithms and new procedures for distinguishing between earthquakes, nuclear explosions and mining explosions of various kinds. Much effort in past discrimination studies has concentrated on extracting various features of the spectrum that are characteristic of earthquakes, nuclear explosions or mine blasts.

One particular spectral feature that characterizes some mining explosions is a modulation of the spectrum introduced by a ripple-fired explosion. A ripple-fired event usually involves detonation of a number of explosions that are often regularly grouped in space and time. Such explosions, known as quarry blasts, have low magnitudes that may be close to those of nuclear explosions that one might monitor under the CTBT. As examples of these kinds of mine blasts, we consider using array data from ARCESS previously analyzed by Der et al (1993). Figure 1 shows a single channel from a typical mine blast, sampled at 40 points per second, with the four main arrival phases identified. We concentrate, in this discussion, on the P_n phase shown in the lower panel. Echoes due to ripple-firing that might be seen in such data for mining explosions would be over .1 seconds and would be aliases of the reflections generated by the firing configurations which probably involve shorter delays. A number of authors have examined various aspects of this problem and have proposed techniques for analyzing these ripple-fired seismic signals. Chapman et al (1992) show reflection patterns for a number of delay-fired configurations and propose a cepstral deconvolution method for estimating the delays. Baumgardt and Ziegler (1988) consider lining up the log-spectra and cepstra for an array and looking for common reflection patterns. Alexander et al (1995) extend this analysis by adding up or *stacking* the spectra. Hedlin et al (1990) propose graphical techniques involving threshold modifications of the time varying log-spectra and cepstra.

The approaches of Alexander et al (1995) and Baumgardt and Ziegler (1988) are based on the premise that a common reflection pattern should appear at each channel on the array. We consider exploiting that idea further by developing a test statistic for detecting a common set of periodic components on an array of suitably detrended log-spectra. In our approach, detrended log-spectra are considered as realizations of stationary processes whose periodic signal components are quefrencies, with periods proportional to delay time differences. Using an approach proposed by Shumway (1971) for detecting a common signal in a collection of stationarily correlated series, an F-Statistic is derived that is proportional

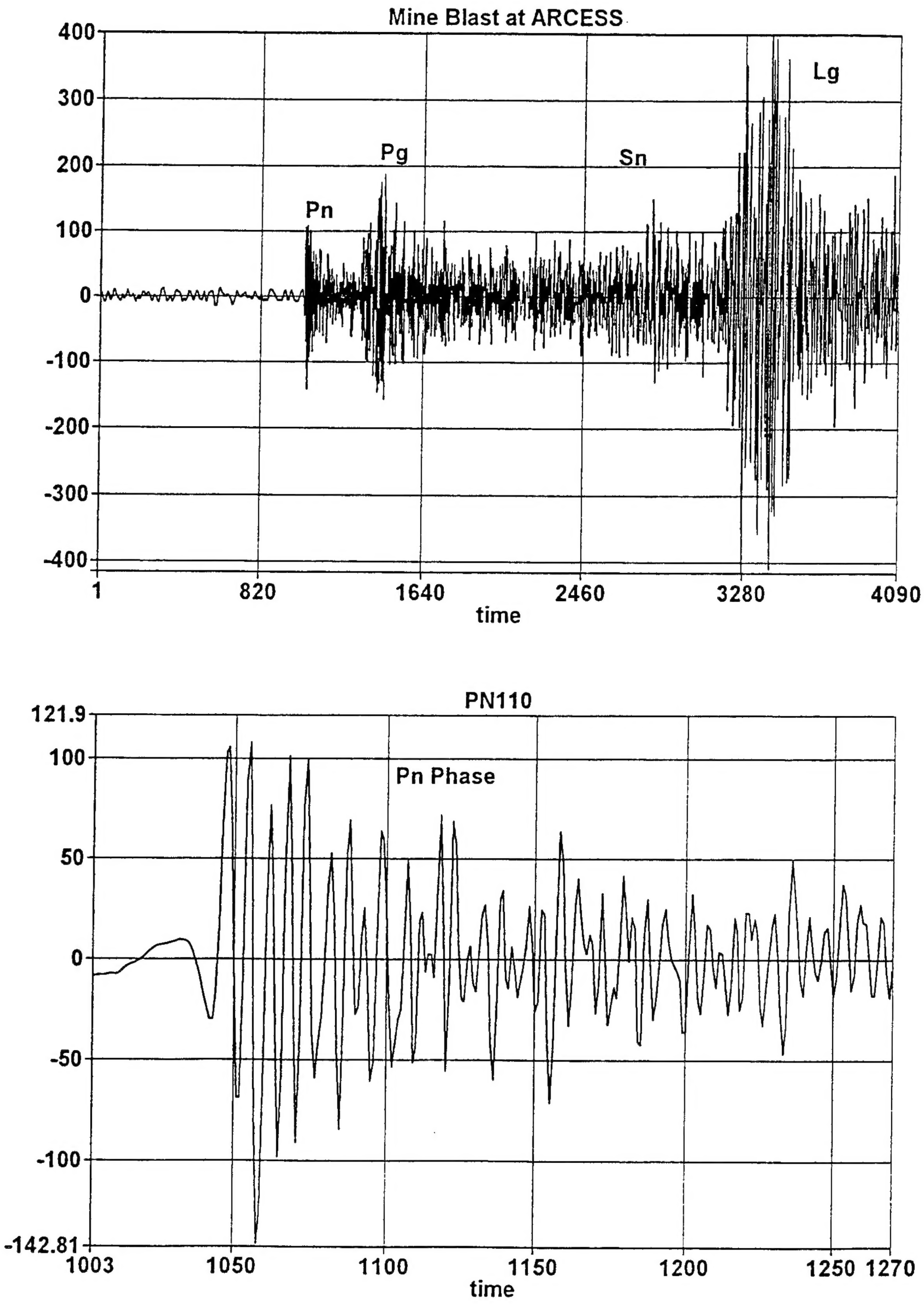


Figure 1: A Mine Blast Observed at ARCESS and the Extracted P_n Phase (40 pts per second).

to the *stacked cepstrum* and the *spectrum of the stacked log-spectra*. Advantages of this cepstral F-Statistic stem from its superior resolving power and the fact that statistical significance can now be asserted for selected delay peaks.

The frequency domain approach proposed above will be compared to a time domain approach that assumes *multiplicative seasonal autoregressive moving-average (ARMA) models* with a fixed regular delay structure on each channel. In general, the reflection delay corresponds to the seasonal lag of the moving average and the duration is proportional to the order. The low- order autoregressive component models the combined effects of source, path and instrument response. Seasonal ARMA models are searched over a number of plausible delays and duration, with the best value of a Bayesian information criterion BIC used to select the best model.

Simulated array data and data from a number of mining explosions, measured at ARCESS in Scandinavia, will be used to compare the time and frequency domain approaches. The organization of the report is to define the multiplicative signal model used in both approaches in Section 2. The frequency domain approach leading to the cepstral F-Statistic is derived in Section 3. Section 4 covers the competing seasonal ARMA search time domain approach and Section 5 uses both techniques to identify possible ripples in a set of 9 mining explosions. We make recommendations for further data analyses in the final section.

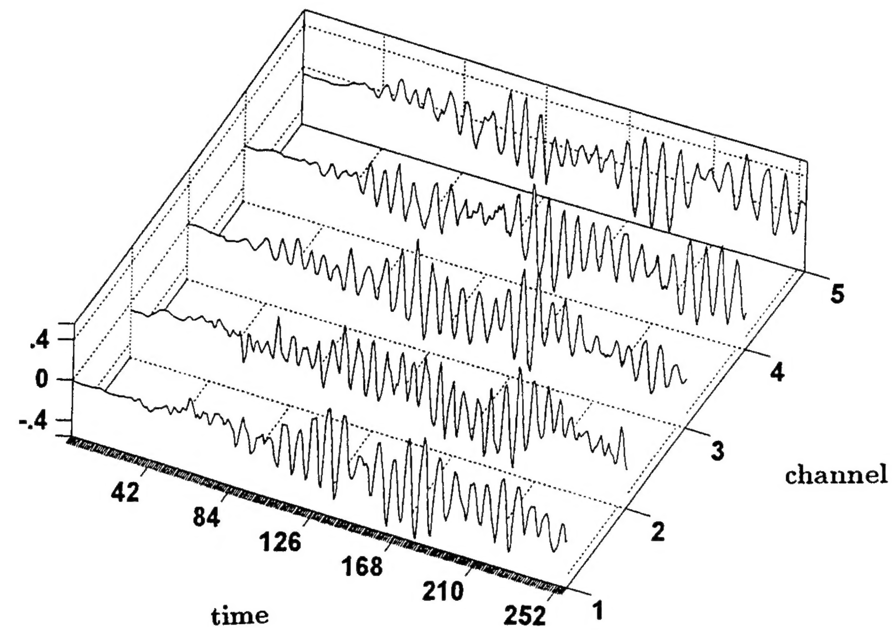
2. Models for Ripple-Fired Signals

A general model that seems to be useful for modeling ripple-firing follows from assuming the presence of a random signal that repeats at delays $\tau_1, \tau_2 \ldots, \tau_n$ with amplitudes $\theta_1, \theta_2, \ldots, \theta_n$ on each channel of an array. This leads to a general model of the form

$$y_j(t) = \sum_{k=1}^{n} \theta_k s_j(t - \tau_k) \tag{1}$$

for the received signal $y_j(t), t = 1, \ldots, T$ at each of $j = 1, 2, \ldots, N$ channels. Here, $s_j(t)$ are input signals, assumed to differ over the array. It is conventional to take $\theta_1 = 1$. For simplicity, we assume signals which are random and uncorrelated between channels with spectral density $P_j^s(\nu)$ at frequency $\nu, -.5 \leq \nu \leq .5$, in cycles per point. This assumption may not always be realistic, but the coherence between elements for the mining explosions here was fairly low although we observed some differences in the spectra between channels. To illustrate, Figure 2 shows a contrived array, generated with a random signal and delays

Stacked plot of Simulated Data



Stacked plot of Simulated Data Log Spectra

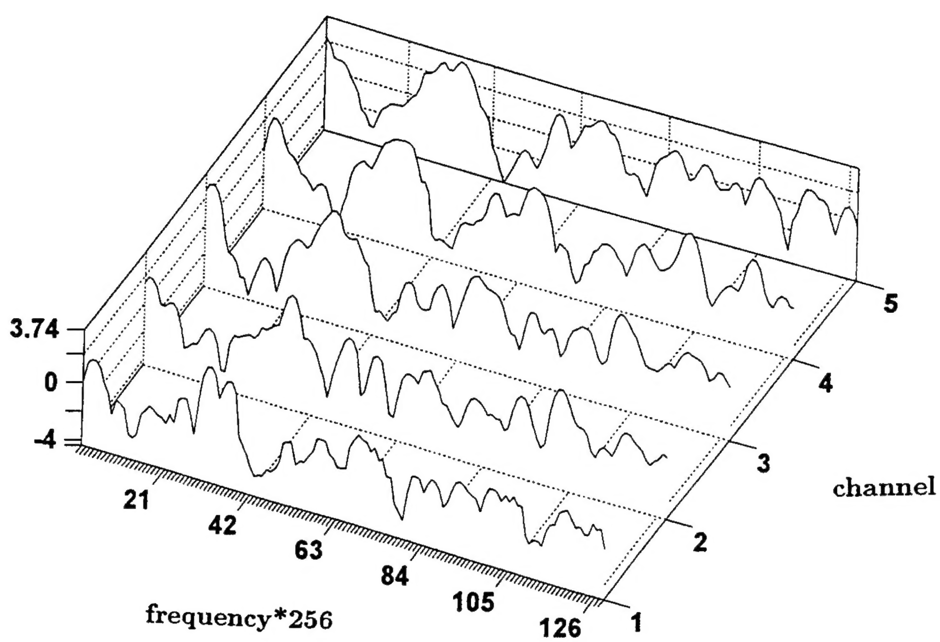


Figure 2: A Contrived Array With Delay Firing (d=8,15,23,30) and the Associated Detrended Log Spectra.

$\tau_1 = 0, \tau_2 = 8, \tau_3 = 15, \tau_4 = 23, \tau_5 = 31$ and amplitudes $\theta_1 = 1, \theta_2 = .9, \theta_3 = .9, \theta_4 = .6, \theta_5 = .7$. Note that the signals are not unlike those contrived series shown in Figure 1.

The model implies that power spectrum of the received signal at channel j has the form

$$P_j(\nu) = |\theta(\nu)|^2 P_j^s(\nu) \tag{2}$$

where

$$|\theta(\nu)|^2 = \sum_{k=1}^{n} \sum_{\ell=1}^{n} \theta_k \theta_\ell \cos[2\pi\nu(\tau_k - \tau_\ell)]. \tag{3}$$

and $P_j^s(\nu)$ is the spectrum of $s_j(t)$. It follows that the overall spectrum on channel j factors into a product of the signal spectrum and a transfer function that is periodic, with quefrencies that are proportional to the time delay differences $\tau_k - \tau_\ell$ for all k, ℓ. It is clear that taking logarithms, say

$$\log P_j(\nu) = \log |\theta(\nu)|^2 + \log P_j^s(\nu), \tag{4}$$

breaks the product into a sum of two terms consisting of the periodic component and the signal spectrum that differs on each channel. Since the signal spectrum, $P_j^s(\nu)$, is generally a smooth function, it is natural to consider the result of fitting a polynomial spline function for the signal to each channel and then adjusting the log-spectrum, in order to obtain a stationary looking series with strong periodicities at the time delay differences. Following through on this procedure leads to the adjusted log-spectra in the lower panel of Figure 2. We note the periodic and stationary appearance of the series; this observation serves as the basis for the frequency domain approach.

In order to develop the time domain approach, we consider a simplified finite parameter model, with the time delays restricted to be multiples of some underlying time delay d, say $\tau_k = kd$. Then, (1) becomes

$$y_j(t) = \sum_{k=1}^{n} \theta_k s_j(t - kd), \tag{5}$$

where the signal satisfies a some low-order autoregressive model, say

$$s_j(t) - \phi_1 s_j(t-1) - \phi_2 s_j(t-2) = w_j(t), \tag{6}$$

with $w_j(t)$ taken as white noise series with common noise variance σ^2. The low-order AR model tends to emulate the smooth spectral component of the multiplicative model, since the spectrum of the received process given in (2) can now be simplified to

$$P_j(\nu) = \frac{|\theta(\nu)|^2}{|\phi(\nu)|^2} \sigma^2, \tag{7}$$

where

$$|\phi(\nu)|^2 = |1 - \phi_1 \exp\{-2\pi i\nu\} - \phi_2 \exp\{-4\pi i\nu\}|^2. \tag{8}$$

and the signal spectrum in (2) is assumed to have the form

$$P_j^s(\nu) = \frac{\sigma^2}{|\phi(\nu)|^2} \tag{9}$$

which emulates the combination of the source, path and instrument spectra. The forms of (5) and (6) also suggest the time domain approach proposed in Section 4.

3. Cepstral Analysis

To follow up on the suggestion in Section 2, based on the additive decomposition (4), we consider computing the logarithm of the spectral estimator at a single channel as shown, for example, in the top panel of Figure 3 for the contrived data. We envision the signal spectrum as a relatively smooth function that can be approximated by a cubic spline with one knot, i.e.

$$\log P_j^s(\nu) \approx a_{j0} + a_{j1}\nu + a_{j2}\nu^2 + a_{j3}\nu^3 + a_{j4}(\nu - \nu_f)_+^3,$$

where ν_f is the knot location and $(\nu - \nu_f)_+^3$ is zero for $\nu < \nu_f$. We may estimate the parameters and consider the *detrended* log-spectrum as

$$\log P_j(\nu) - \log P_{s_j}(\nu) = \log \frac{P_j(\nu)}{P_{s_j}(\nu)}.$$

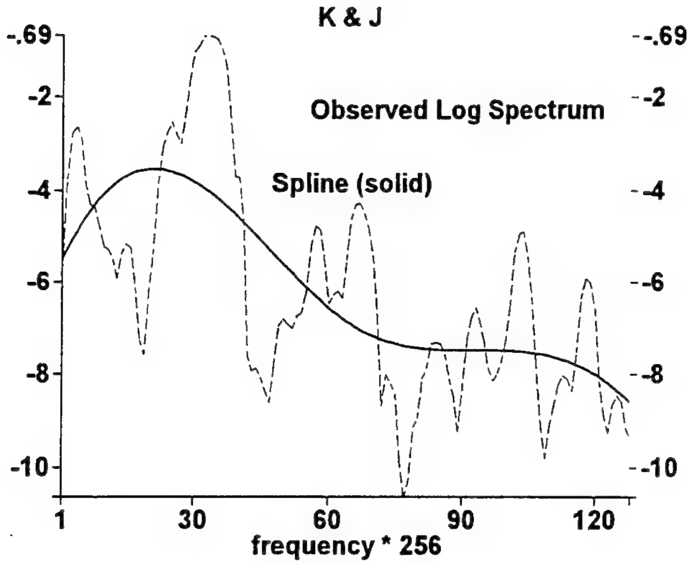
The detrended log-spectrum is shown in the lower panel of Figure 3 and seems clearly like a stationary process with periodic components that one could isolate by computing the spectrum of the log-spectrum, i.e. the cepstrum. Looking back at the bottom panel of Figure 2 verifies that all channels seem to carry the same periodicities and are relatively stationary.

This motivates an approach similar to that given in Shumway (1971), where the Fourier transform, say

$$Q_j(d) = FT\left\{\log \frac{P_j(\nu)}{P_{s_j}(\nu)}\right\} \tag{10}$$

is regarded as behaving like the transform of a stationary process in the delay d at each channel so that one may write the signal plus noise model

$$Q_j(d) = S(d) + V_j(d). \tag{11}$$



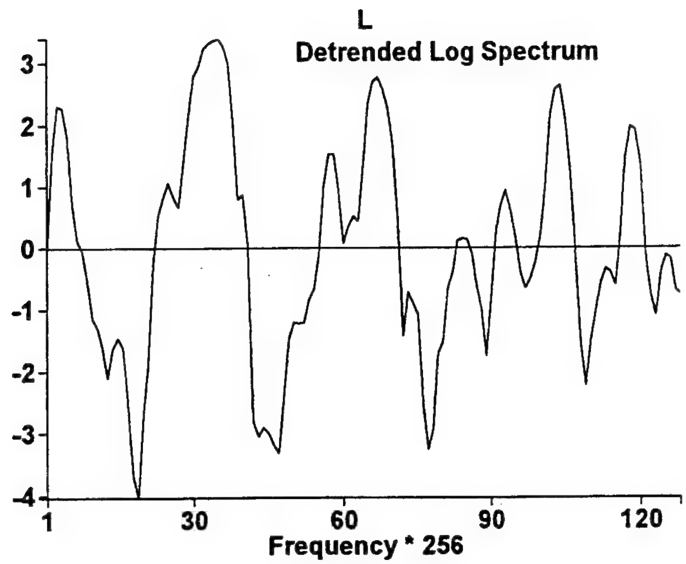


Figure 3: Observed Log Spectrum and Spline-Detrended Log Spectrum.

Here, the signal transform is fixed and unknown and the noise $V_j(d)$ has a complex Gaussian distribution with mean 0 and variance $\sigma^2(d)$ at delay d. Then, motivated by the classical approach to detecting a signal in N stationarily correlated time series, we note that testing the hypothesis $S(d) = 0$ leads to an F-Statistic involving the *stacked cepstrum*

$$SCT(d) = \sum_{j=1}^{N} |Q_j(d)|^2 \tag{12}$$

and the spectrum of the *stacked log spectra*, say

$$SCM(d) = N|\bar{Q}(d)|^2, \tag{13}$$

where

$$\bar{Q}(d) = N^{-1} \sum_{j=1}^{N} Q_j(d) \tag{14}$$

is the mean Fourier transform of the array log-spectra. Figure 4 shows a mean of the array log-spectra and we note that the common periodicities observed in the bottom panel of Figure 2 are enhanced in the stack. An important quantity involved in the optimal detection statistic is the *error cepstrum*, defined as

$$\begin{aligned} SCE(d) &= \sum_{j=1}^{N} |Q_j(d) - \bar{Q}(d)|^2 \\ &= SCT(d) - SCM(d) \end{aligned} \tag{15}$$

which is a measure of the extent to which the individual channel transforms differ from the mean transform. It can be interpreted as the *cepstral noise* component. The F-Statistic resulting from the signal detection hypothesis is given by

$$F_{2,2(N-1)}(d) = (N-1)\frac{SCM(d)}{SCE(d)} \tag{16}$$

and can also be interpreted as a cepstral *signal to noise ratio.* The subscripts refer to an F distribution with 2 and $2(N-1)$ degrees of freedom.

The information above can be summarized in a *cepstral analysis of variance (ANOVA)* table as shown following Figure 4.

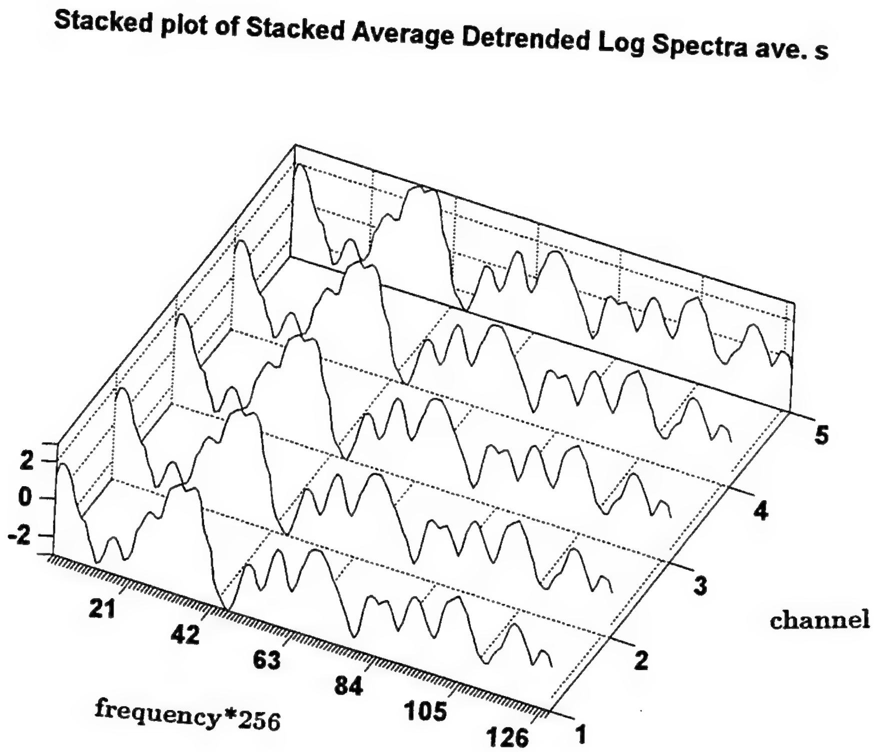


Figure 4: Average of Detrended Log Spectra.

Table 1: Cepstral ANOVA at Delay d

Source	Cepstral Sum of Squares	df	Mean Square
Signal	$SCM(d) = N\|\bar{Q}(d)\|^2$	2	
Noise	$SCE(d) = \sum_{j=1}^{N} \|Q_j(d) - \bar{Q}(d)\|^2$	$2(N-1)$	$\hat{\sigma}^2(d)$
Stack	$SCT(d) = \sum_{j=1}^{N} \|Q_j(d)\|^2$	$2N$	

Table 1 shows the partition of the total cepstral sum of squares or stacked spectrum into components corresponding to the signal and noise. Note that the total cepstrum is exactly the *sum-stack* proposed by Alexander et al (1995), computed by adding up the separate cepstra shown in Figure 5. Alexander et al have also considered the product-stack which does not appear to have any identifiable statistical properties and we do not analyze it here. It is clear that the sum-stack will not reflect the common signal components as well as either the cepstral component due to the signal (see Figure 4 for the log-spectral stack) or the F-Statistic (16). Note also that the estimated noise cepstrum is computed from Table 1 by

$$\hat{\sigma}^2(d) = \frac{SCE(d)}{2(N-1)} \tag{17}$$

Figure 6 shows the components of the cepstral variance and the F-Statistic corresponding to the contrived data shown in Figure 2. The solid line in the upper panel represents the total or sum-stacked cepstrum of Alexander et al (1995), i.e. $SCT(d)$ in the equations and Table 1. Note the strong component appearing delays 8, 15, 23, 30 and 36 points as may be compared with the known true delays 8, 15 23 and 31 points. Note that the true time delays would imply quefrencies of the form 7, 8, 15, 16, 23 and 31 points respectively. The noise cepstrum, $SCE(d)$, is also shown as the dotted line in the upper panel and we note that it is quite small for this simulated example. The cepstral F-Statistic, shown in the lower panel of Figure 6, provides a statistical level of significance for the various peaks and we note that the significant peaks are 8, 16, 23 and 30 points so that the smallest of the larger peaks at d=36 in the stacked cepstrum is not significant. All peaks are significant at a false alarm rate of .001. In general, since there are often a large number of delays of interest, one should insist on at least .01 as a level of significance.

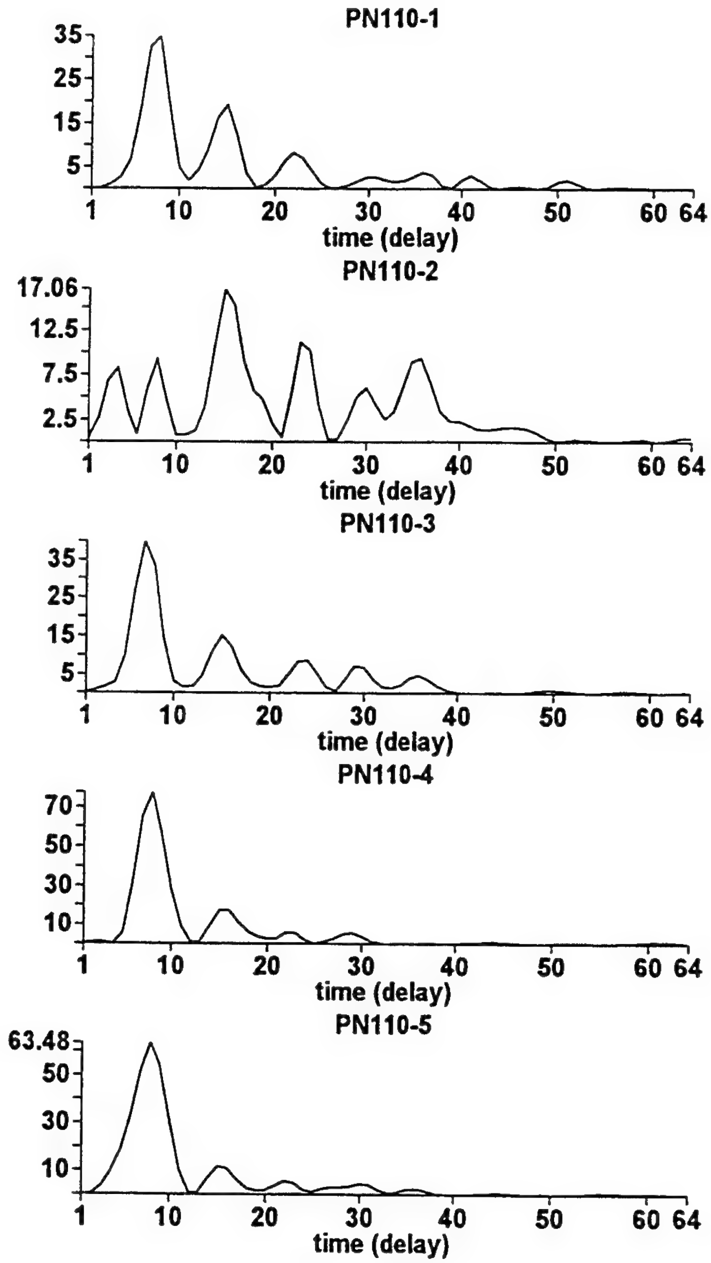


Figure 5: Cepstra of Contrived Array Data (Delay in pts).

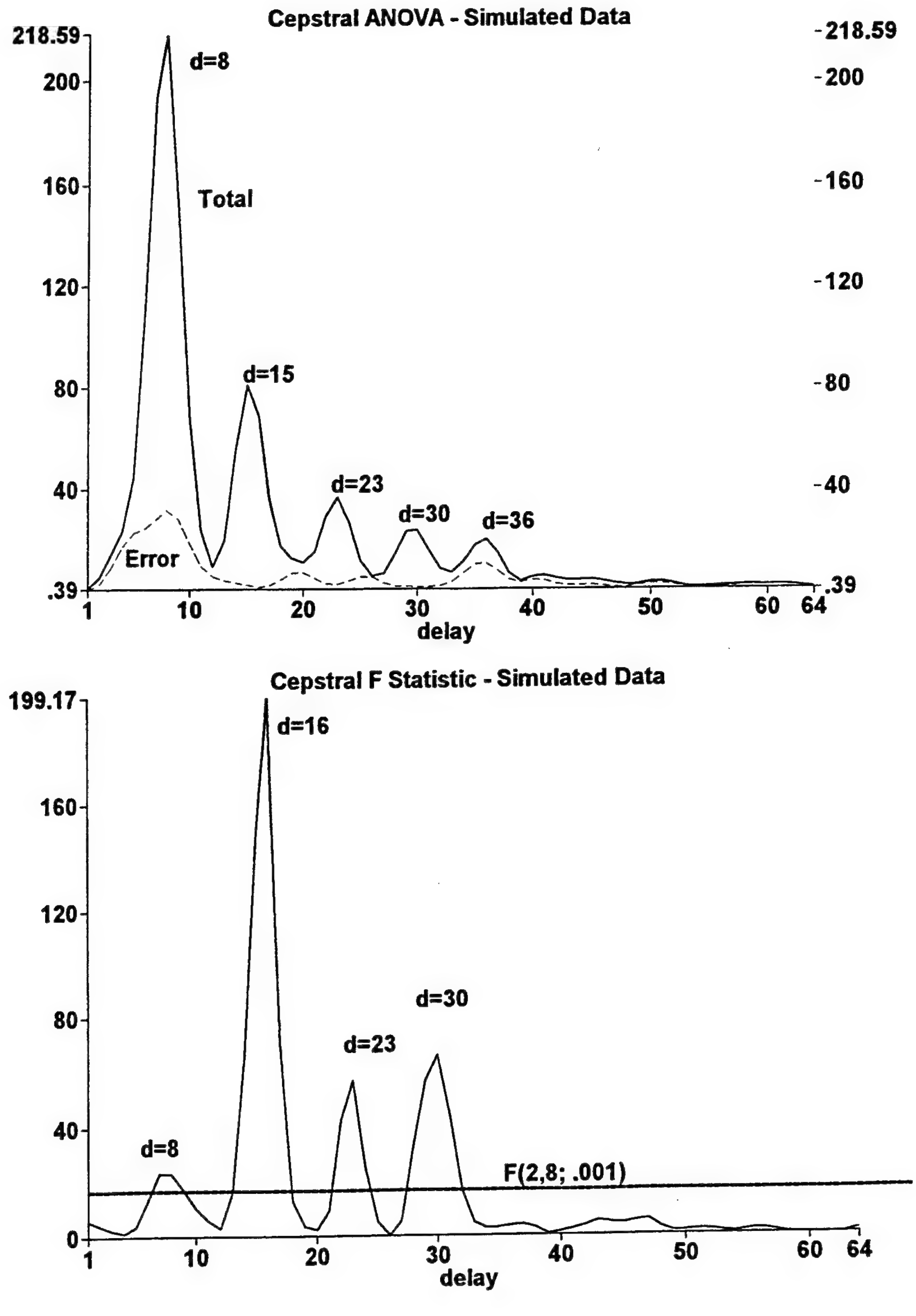


Figure 6: Cepstral Analysis of Variance and F-Statistic for Contrived Data (Delay in pts).

4. Seasonal ARMA Searching

The cepstral approach is an example of a nonparametric procedure since it requires only that the signal spectrum be relatively smooth and that we only want to identify the periodicities associated with the time delay differences. One may also consider more parametric approaches where the problem can be identified as one of estimating the $\theta_1, \theta_2, \ldots, \theta_n, \phi_1, \phi_2$ and σ^2, using the received series $y_1(t), \ldots, y_N(t)$ for $t = 1, \ldots, T$ and the model as given by (5) and (6). Parametric approaches will also involve estimating the number of reflections n and settling on a time delay d. If the structure of the reflection sequence is unknown, one can also consider multiple deconvolution techniques as in Der et al (1987). Single channel deconvolution techniques may also be applied. Approaches based on a frequency domain to the likelihood function are often useful, as in Hannan and Thomson (1974) or in Shumway and Blandford (1978). Several preliminary trials of these general methods seem to be ineffective for the current problem where one has a large number of unknown reflections with unknown delays. The parametric model in (5) and (6) seems to offer a plausible alternative to the nonparametric cepstral approach and we investigate this methodology here. Note that Shumway and McQuarrie (1994) investigated this technique in the single channel case.

Minimizing the sum of squared errors for specified values of n and d leads to the objective function

$$SSE(\theta_1, \theta_2, \ldots, \theta_n, \phi_1, \phi_2) = \sum_{j=1}^{N} \sum_{t=nd}^{T} w_j^2(t), \tag{18}$$

which maximimizes the log likelihood and we may estimate σ^2 as

$$\hat{\sigma}^2 = \frac{1}{NT'} \sum_j \sum_t \hat{w}_j^2(t), \tag{19}$$

where the nonlinear optimization only involves $T' = N(T - nd + 1)$ residuals. In order to select a model, we choose n and d as the joint minimizers of the *Bayesian Information Criterion (BIC)*, say

$$BIC(n, d) = \log \hat{\sigma}^2 + \frac{(n+2)\log(NT')}{NT'}. \tag{20}$$

For a summary of the nonlinear Gauss-Newton estimation procedure applied to the repeated measures ARMA model, see Shumway(1988).

To give an example, consider searching the contrived data in Figure 2 for the best fitting seasonal ARMA process. It is convenient to limit the number of reflections to the

possible range $1 \leq n \leq 6$ and the delays to the range $3 \leq d \leq 12$. We begin with $d = 3$ so as not to confuse the delays with the first two lags of the autoregressive part. Figure 7 shows the resulting values of BIC and we note that there are a number of local minima, mostly occurring at $d = 8$. An approximation to the correct model is $n = 5, d = 8$ which also is the global minimum of BIC in Figure 7. The time domain approach has more difficulty estimating n in this case, with local minima occurring for $n = 1, 2, 3$ and $d = 8$. Note also that the region defined by $n = 5, 6, d = 7$ is also a possible model. In summary, there are more possible interpretations for the ultimate model implied by the time domain analysis and few approximate statistical significance tests are available for the number of reflections. One might consider testing against a model with $n = 0$, but we did not do so because of the number of possible alternatives.

5. Analysis of Kola Mining Explosions

We consider applying the frequency and time domain methods to a population of 9 mining explosions from the Kola Peninsula (situated in the Russian Arctic), all at the HD9 quarry, observed at 5 channels of the ARCESS array in northern Norway (see Der et al, 1987). The mini-array consists of a three-component array augmented by two vertical instruments from the C-Ring.

To begin, Figure 8 shows the P_n phase from event number 110 observed at ARCESS and we note that the detrended log-spectra show evidence of periodicities. Figure 9 shows the original log-spectrum observed at a single channel along with the fitted spline which contained a single not at $\nu_f = .25$ cycles per point, or half the folding frequency. Since we are considering data at 40 points per second, the folding frequency is 20 Hz and the knot occurs at 10 Hz. Performing the cepstral analysis of variance and computing the F-Statistic in Figure 10 indicates the presence of statistically significant peaks at 24 and 34 or .60 and .85 seconds. There are also peaks at .18 and .35 seconds of lesser (.05 level) significance. One might tentatively hypothesize ripple-firing with delays of about .18-.25 seconds. It is interesting also to check the noise before the signal for possible delays that are not due to ripple-firing. Figure 11 shows the cepstral analysis of variance for this case and we only identify some very low quefrencies at a very low significance level (.05). Applying the time domain approach, as in Figure 12, shows possible consistent delays at delay 7 or .18 seconds and a secondary set of minima at delay .28 seconds.

We have also analyzed the P_n phases from eight additional mining explosions and the results are shown in Table 2. Only peaks that are significant at level .01 are quoted. The

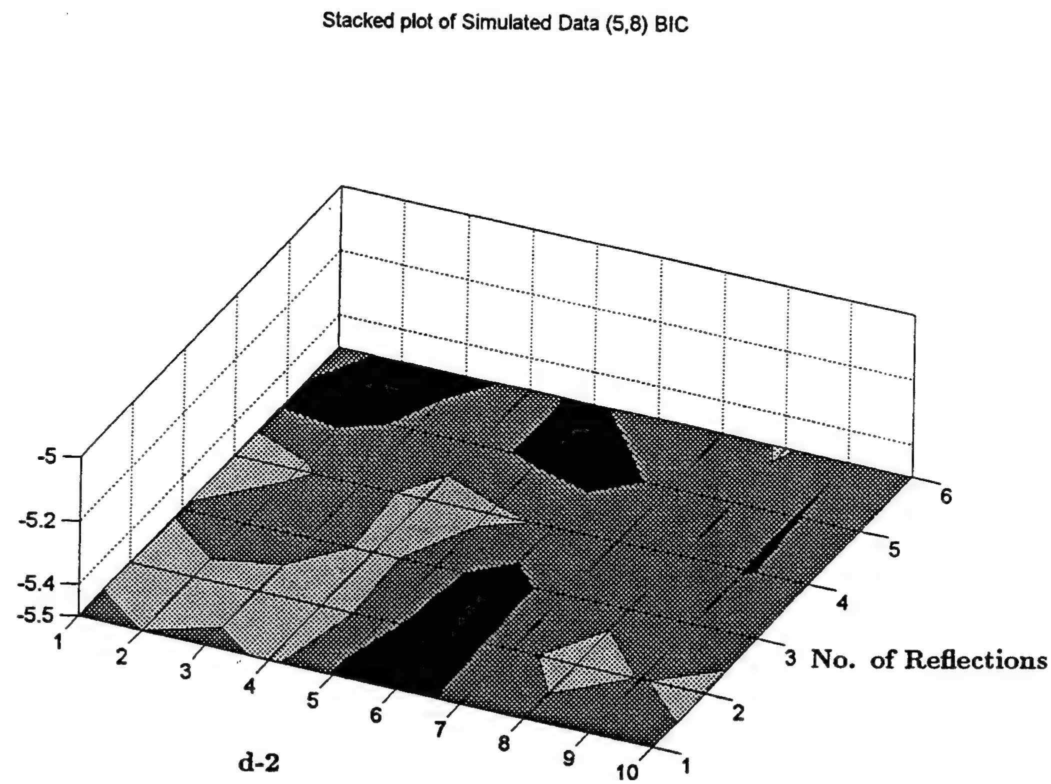
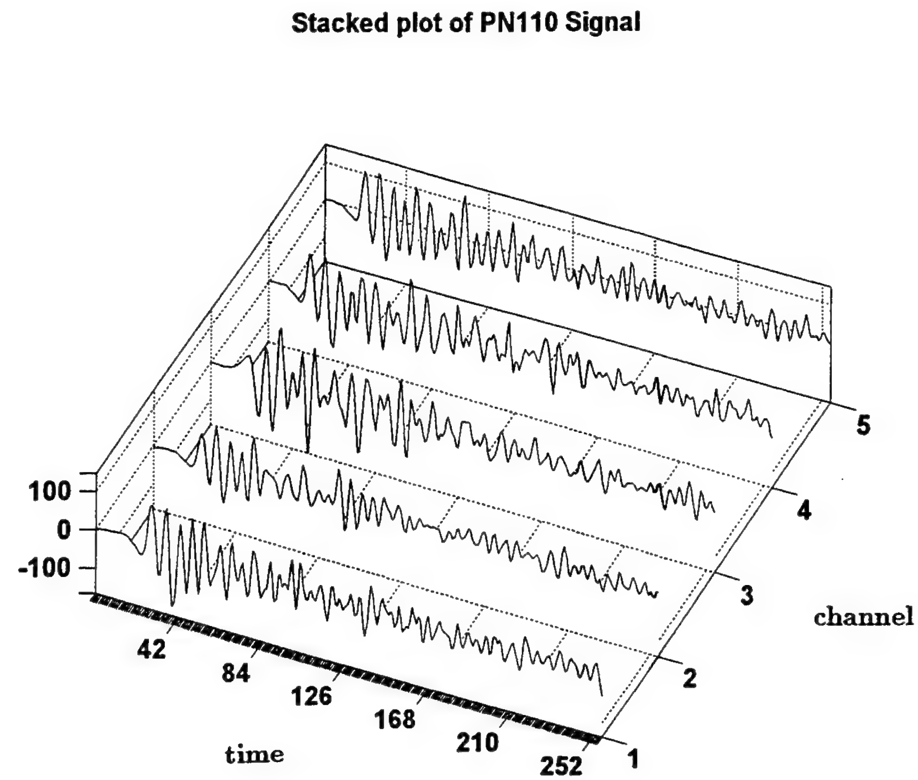


Figure 7: BIC Contour For Contrived Event (delay=d-2 vs number of reflections n, darker denotes smaller BIC)



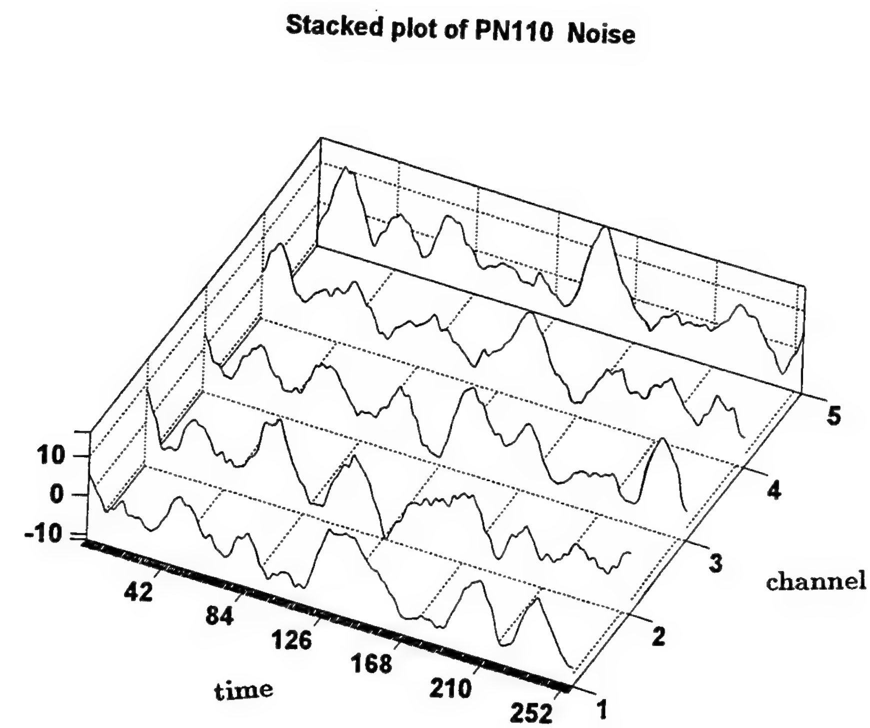
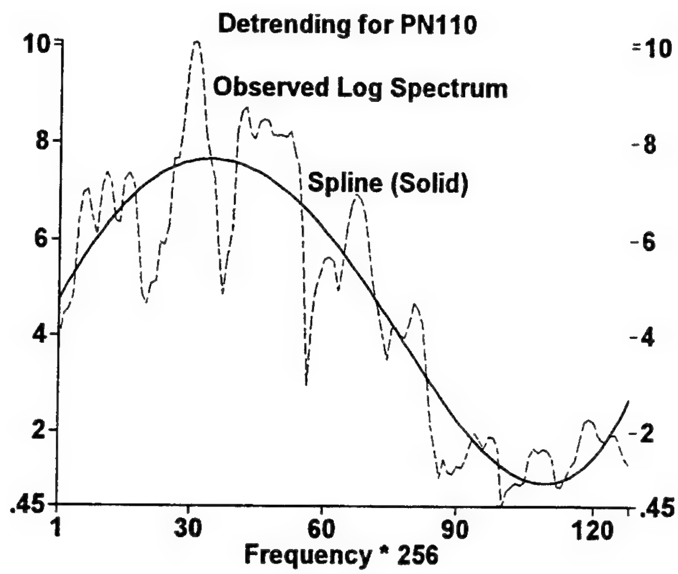


Figure 8: Array Recordings of P_n Phases for Event 110 Recorded at ARCESS Compared With Noise Preceding Signal (40 pts/sec)



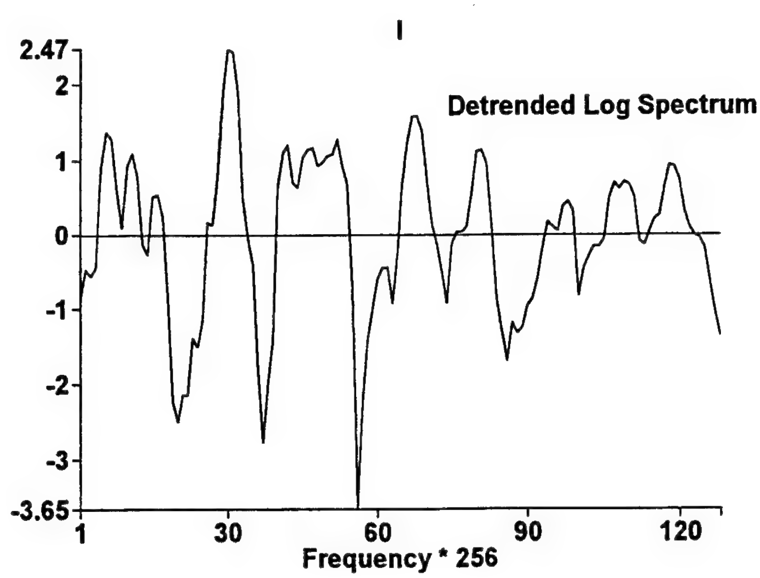


Figure 9: Observed Log Spectrum and Spline-Detrended Log Spectrum for P_n Phase at a Single Channel, Event 110.

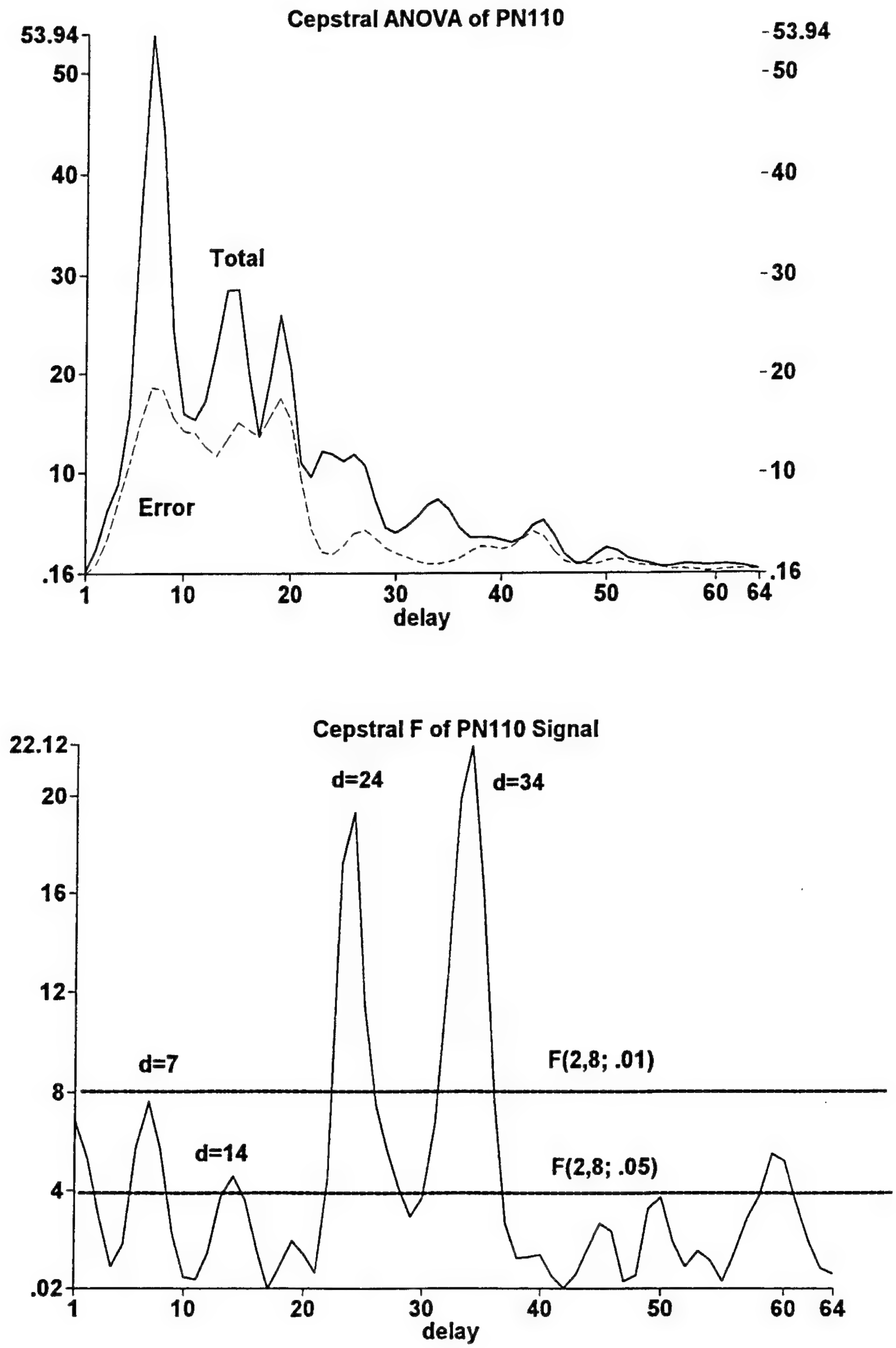


Figure 10: Cepstral Analysis of Variance and F-Statistic for P_n Phase, Event 110 (Delay in pts).

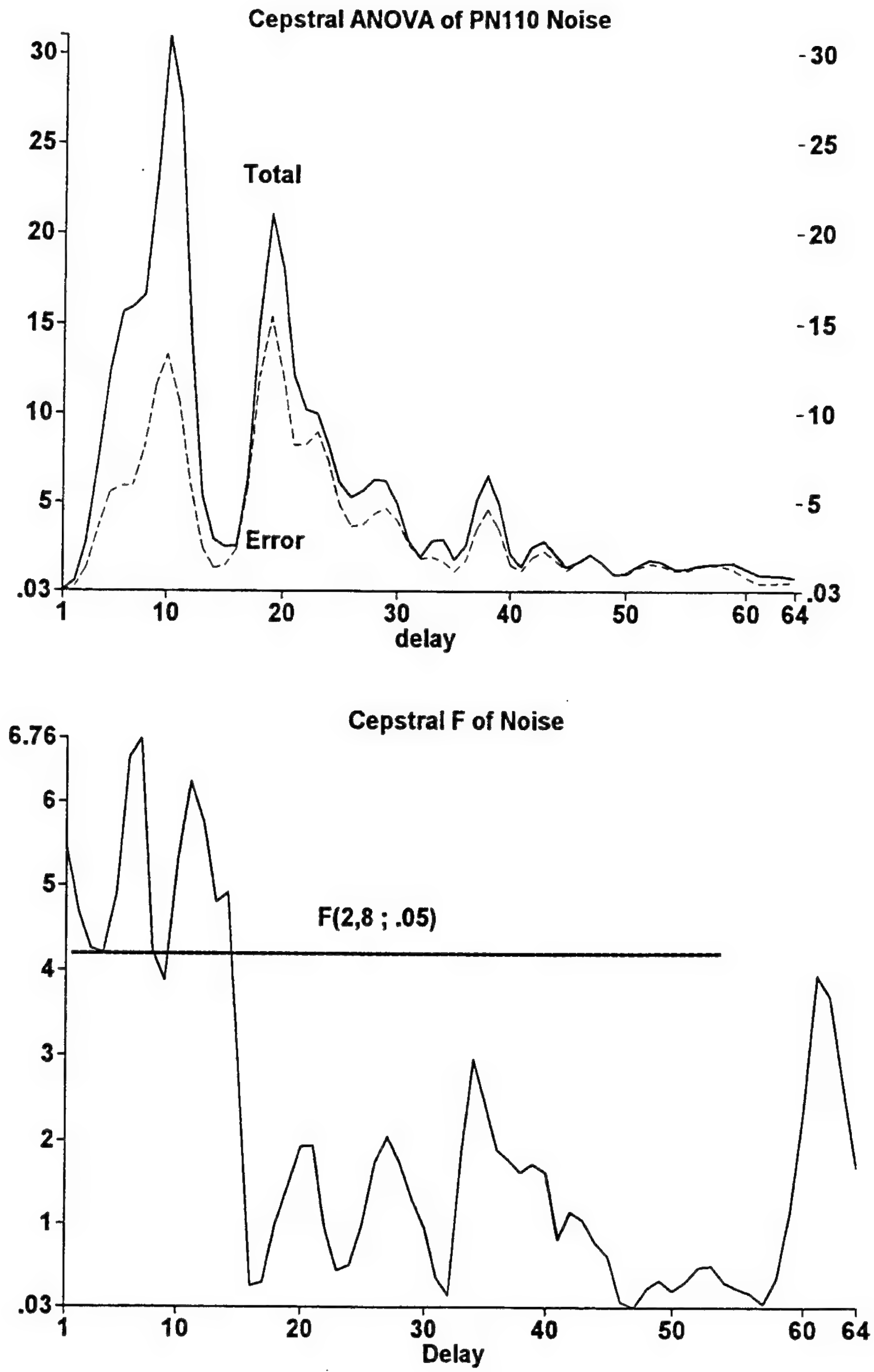


Figure 11: Cepstral Analysis of Variance and F-Statistic for Noise Preceding the P_n Phase, Event 110 (Delay in pts).

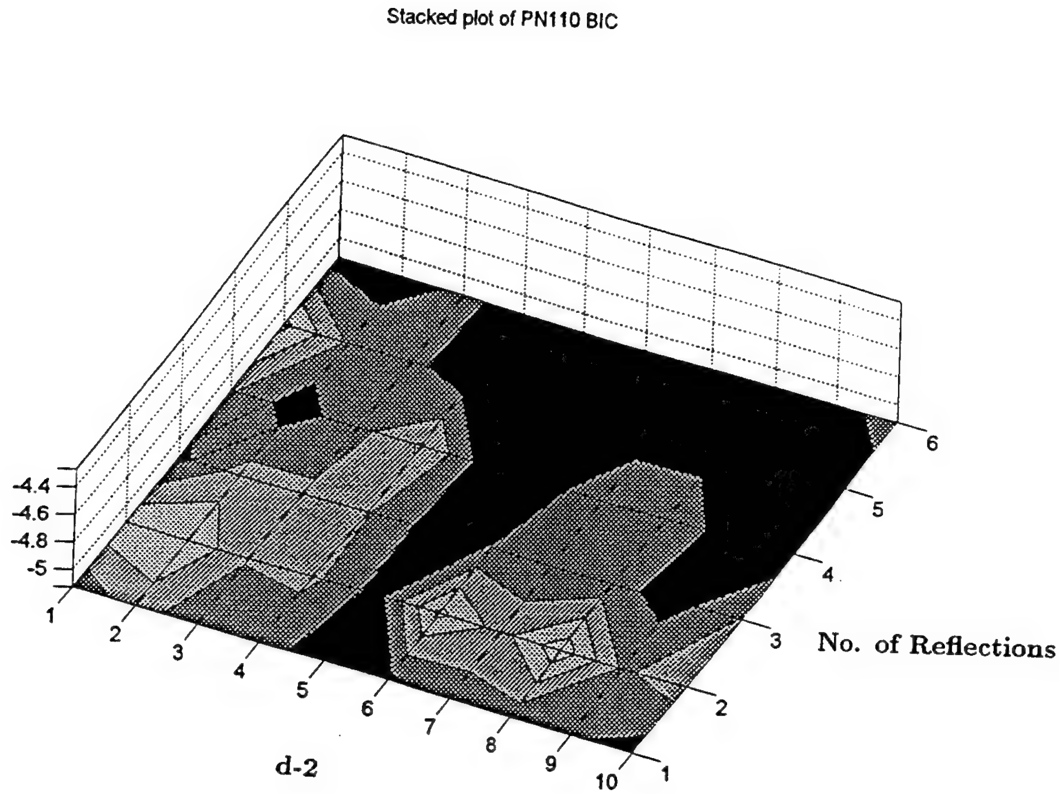


Figure 12: BIC Contours For P_n Phase, Event 110 (delay=d-2 vs number of reflections n, darker denotes smaller BIC).

results are mixed, with the time and frequency domain results not matching in a number of cases. Analyzing the L_g phases produced results that were roughly consistent with the P_n analyses but several cases such as events 054 and 066 showed no signs of ripple-firing.

Table 2: Estimated Time Delays for HD9 Explosions (in seconds)

Event	F-Statistic		SARMA Search
	P_n	L_g	P_n
054	.06	-	.075,.125
066	.25,.58	-	.05
110	.60,.85	.30,.85	.18,.23
147	.18,.50	.18	.18
182	.50, 1.08	.53, 1.08	.15
219	.38,.60,.75	.28,.38	.18
246	.30, .58, 1.23	.33, .80	-
282	.30,.50,.63,.78, 1.13	1.53, 1.98	-
285	.58,.65,.98	.18,.48	.18

6. Discussion

We have developed frequency and time domain approaches to detecting ripple-firing and have tested these methods, both on simulated data and on very small arrays of real data. In general, the frequency domain method, leading to the cepstral F-Statistic, is preferred because the presumed irregularities that will be present in most ripple-fired signals dictate a more nonparametric approach that does not assume a given delay structure. These irregularities are due, in part, to the geometry of the firing pattern and the limitations of sampling at rates comparable to 20 Hz. The cepstral F-Statistic also achieves a resolution advantage due to dividing by the noise cepstrum. Furthermore, the F-Statistic provides a threshold for deciding whether a given delay is statistically significant.

The last comment above suggests that the F-Statistic can be easily incorporated into an automatic detection procedure through which one can tag the delays that are statistically meaningful and ignore those that are not. In this sense, it can be used as an on-line method for detecting ripple-firing as a part of an automatic monitoring system. One simply incorporates the statistic into the automatic processing scheme since it only involves

using the detrended log-spectra and the averaging operations that will produce the entries in the analysis of variance Table 1.

The question of whether currently configured array data can be used to detect ripple-firing well enough to separate mining explosions from those of other kinds has not been answered in this report. During the next phase of the project, we intend to test the cepstral F-Statistic methodology on more events from larger arrays. Larger arrays are potentially useful since they will presumably provided a greater enhancement of the common periodicities due to ripple-firing.

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